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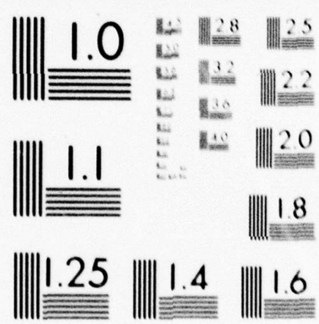

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SEMIAUTOMATIC EXTRACTION OF ROADS FROM AERIAL PHOTOGRAPHS

Final Technical Report

by
Dr.-Ing. W. Kestner

June 1978

EUROPEAN RESEARCH OFFICE
United States Army
London England

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Prof. Dr.-Ing. H. Kazmierczak
FIM/FGAN, Breslauer Str. 48
7500 Karlsruhe 1, F.R. Germany

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Three different methods have been developed for the semiautomatic extraction of roads from aerial photographs. The interpreter has to initialize the procedures by defining parameter values and starting points on the roads. The results of the extraction procedures are displayed immediately for control and necessary correction by the interpreter.

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All three methods are described in principle, while one of them is described in detail. Test material for the methods had been provided by USAETL. Test results are shown and serve to explain the abilities and limits of the extraction methods. An assessment of the methods and discussions of further work conclude this report.

Contents:

Preface

The Research reported in this document has been made possible through the support and sponsorship of the U.S. Government through its European Research Office. This report is intended only for the internal management use of the Grantee and the U.S. Government.

The work was performed during the period Mai 15, 1977 through April 15, 1978.

1. Definition of the Problem

Nowadays there is a big and still increasing demand for fast and precise techniques of aerial photo interpretation. For many sciences, authorities, and individuals, the use of information gained by aerial photo interpretation is the most reliable and up to date basis for their tasks. The extraction of object data (such as the shape or the location of an object) from aerial photos is related to the interpretation problem. Considering the problem of map production a restricted but well known set of objects has to be recognized in and extracted from aerial photographs for compilation into a map. The visual recognition and manual extraction of the contours of the major roads from one aerial photograph with a size of 9' by 9' takes approx. 2 to 4 hours.

An effort has been made to automate this problem as far as possible in order to speed up and ease the extraction of data from photographs. The problem of recognizing and classifying is left to the human while the time consuming task of finding the exact contour lines will be accomplished semiautomatically. The research task to be described below can be stated as follows: Given grey level aerial photographs taken from high altitudes at scales from 1:20 000 to 1: 74 000, develop automatic methods for use in an interactive image interpretation system, which extract the coordinates of roads fast and precisely under interpreter control.

2. Automatic versus interactive extraction methods

A review of several well known algorithms for automatic object extraction and object recognition (contour filtering, contour tracing, object filtering, correlation techniques, multispectral object recognition etc.) revealed that a fully automatic solution of the problem is not yet possible mainly for the following reasons:

- the algorithms are not flexible and adaptive enough
- the results are not acceptable in case of noise and distortions
- the classification power is not satisfying in case of complex real world objects
- most algorithms require too much computing time

Interactively controlled semiautomatic methods seen to be more promising. Clearly, the amount of interactive control to be provided by the operator (e.g. an image interpreter) should be minimized. The following procedure of interactive extraction of roads from photographs is proposed:

- digitize the photograph
- display the digitized photograph on an image display with interactive devices (track ball, light pen etc.)
- recognize visually a (part of a) road
- indicate the starting point of the road on the display screen
- call the algorithm to be used for the extraction of the road
- set parameters (e.g. thresholds) for the algorithm
- let the algorithm work and display the results immediately
- decide visually whether the results are acceptable or not
- interrupt the algorithm if neccessary and decide on new steps
- assemble the results and perform manual or automatic postprocessing.

The integration of the interpreter with his outstanding ability to solve the classificatory part of the problem is considered to be a big advantage. In order to speed up the computational part of the problem, the automatic methods are not very complex. Three methods have been developed to accommodate the differing appearrance of the different roads. All methods will be described in principle, while the third one will be explained completely and in detail (see also [1, 2, 3]).

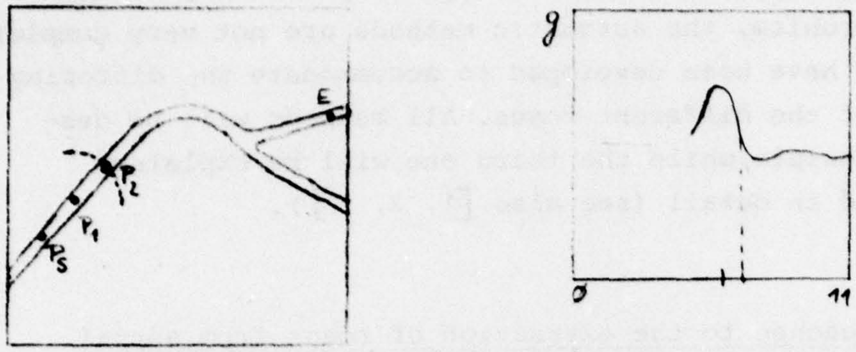
3. Three approaches to the extraction of roads from aerial photographs

3.1 Incremental method

The incremental procedure with adaptive parameters is well suited for clearly visible roads with little distortions and occlusions. It is not affected by local changes of the grey level or width of the road, nor by crossroads or curves, as it follows the course of the road step by step checking the grey level situation at each step and adapting its parameter values continuously to the values actually found.
The interpreter has to mark the starting point for the method at a clearly visible part of the road. He may then set initial values for the parameter's grey level tolerance, width of the road, length of a step etc. Standard values will be used as defaults for these parameters. Now the algorithm tries to follow the road from the start automatically. Suppose that the points p_S and p_1 have been found on the road (see fig. 1a). The algorithm continues as follows:

- connect p_S and p_1 by a straight line
- prepare the next step by marking a point p_2 on this line at a distance of the initial length of a step beyond p_1 (see fig. 1a)
- evaluate the coordinates of all points of a section of a circle through p_2

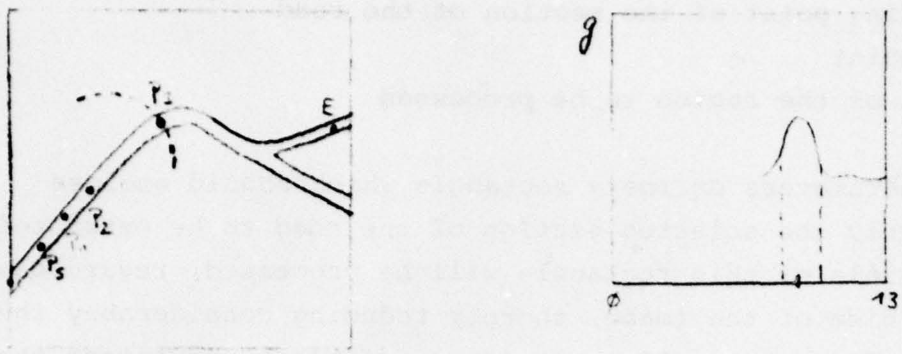
- compile the grey levels of all these points into a grey level diagram (cross section of the grey level situation at point p_2, see fig. 1b)



a) b)

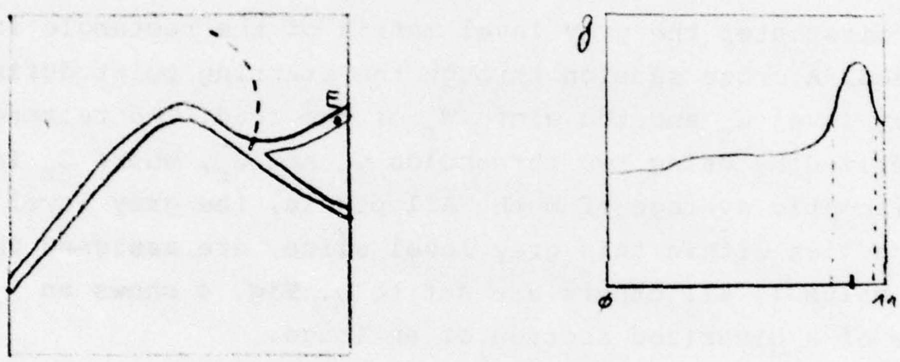
figure 1

- analyze the grey level diagram to discover features of the road: dark road with bright suroundings ("valley" in the diagram), bright road with dark suroundings ("mountain" in diagram) etc.
- compare the candidate features of the road with the actual width tolerance of the road. In case of compliance take the location of the grey level maximum (or minimum in case of dark road) as the next point p_2 on the road
- if there is more than one candidate which fulfills the specifications of the features of the road decide for one of them. Criteria for this decision are:
  i) the direction towards the end of the part of the road, if the end point has been set
  ii) the persistance to go on straight
  iii) always turn right, but store the coordinates for later processing of the other candidates
- if the road proves to be straight, increase the length of the steps until the next curve will be reached (see fig. 2a and b). A curve of the road implies candidate features of the road which are not located near the centre of the grey level diagram (see fig. 3a and b). In this case the length of the steps is decreased automatically.
- if no candidate features of the road are found, ask for help.



a) b)

figure 2



a) b)

figure 3

The points of the road which have been accepted by the algorithm are displayed immendiately for visual control by the interpreter. Correcting and completing of the extracted roads can readily be performed.

3.2 Binarizing method

The area binarizing and interpolation method attempts to cope with disturbed and partially occluded roads. To initiate the procedure, the operator has to set the following parameters (e.g. with a trackball):

- starting point of the section of the road
- end point
- width of the region to be processed

These parameters define a rectangle which should enclose completely the selected section of the road to be extracted. Only pixels of this rectangle will be processed, regardless of the size of the image, thereby reducing considerably the amount of computing time. It is an additional advantage that the operator can avoid ambiguities by choosing an adequate rectangle.

In the first step the grey level matrix of the rectangle is binarized. A cross section through the starting point defines the grey level G_r and the width W_r of the road. The rectangle is binarized by using two thresholds G_r^+ and G_r^-, where G_r is the arithmetic average of both. All pixels, the grey level of which lies within this grey level slice, are assigned the binary value 1, all others are set to 0. Fig. 4 shows an example of a binarized section of an image.

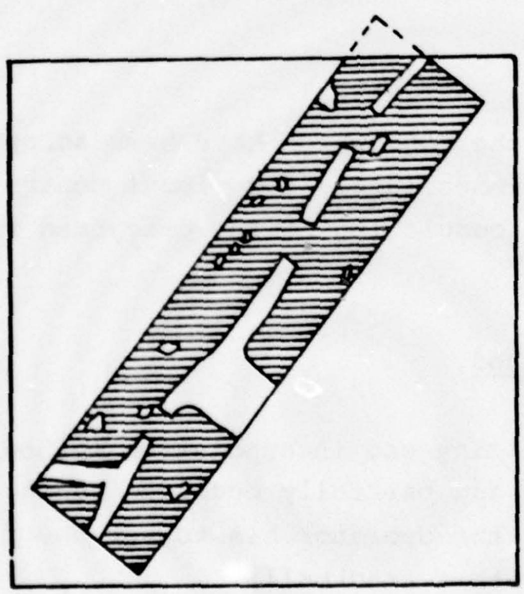


Figure 4: Binarized rectangle

After binarization the picture consists of several areas not connected to each other. The next step is to eliminate those areas definitely not belonging to the road. One criterion, that is used to decide this, is the shape. All parts of the road are presumed not to exceed the width W_r plus a certain tolerance value. A measure for the width of an area is given by ROSENFELD'S distance transform [4]. The distance transform assigns a value to each pixel of an area according to the distance of this pixel from the nearest border of the area. After the distance transform has been performed, all areas whose width exceeds W_r are deleted (see fig. 5). Areas that are thinner than W_r are preserved because parts of the road might be partially hidden.

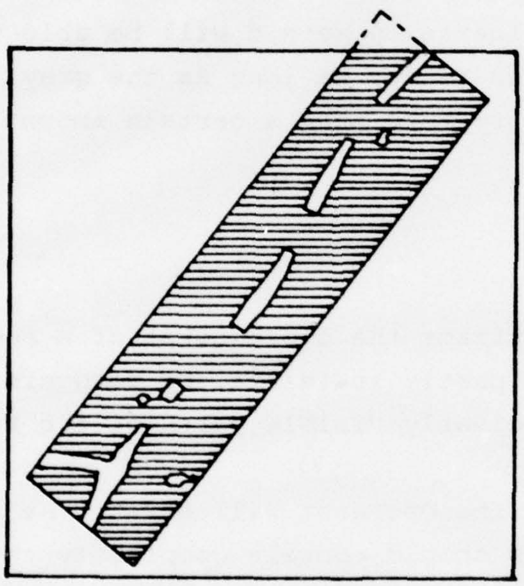


Fig. 5: After deletion of big areas

After deleting all inappropriately shaped areas the next step will decide which of the remaining areas will be termed parts of the road, and will interpolate the gaps between these parts. This can be done beginning at the start and the end point and proceeding towards each other. If a gap is reached, all remaining parts in the nearer environment are considered as candidates for the most probable continuation of the road. The probability of a candidate is based on the following criteria:

- the elongation of the candidate
- the length of the gap to the candidate
- the direction of the gap compared to the global direction of the road

If the interpolation fails to select the appropriate candidate, the interpreter can correct the decision. Thus, with interactive aids, the binarizing method will be able to extract curved and distorted roads, as long as the grey level along the roads do not vary more than a certain amount.

3.3 Random method

This method will extract the coordinates of a section of a road even if it is partly invisible, by recognizing only a few points of the clearly visible parts of the road.

In the first step, the operator will define the area of interest interactively which should contain completely the section of the road to be extracted. The width of the rectangular area of interest may be small, medium, or large, depending on the curvature of the road (see fig. 6a).

This rectangular area is divided into n slices of equal size. Points of the road will only be searched on the n+1 sample lines intersecting the rectangle. The first line containing P

can be used to supply information about the actual grey level and the width of the road if these parameters are not defined interactively. These two parameters are not adapted while the algorithm proceeds. The grey level diagrams of the intersecting lines will be searched for parts which most likely belong to the road. To facilitate this search, all points of the sample lines are transformed into a normalized coordinate system (see fig. 6b). This is done for two reasons mainly:

- to minimize access to mass storage, as the complete picture matrix does not fit into the working storage of the computer
- the search procedure for the grey level diagrams of the sample lines is simplified, if applied to points of a normalized coordinate system

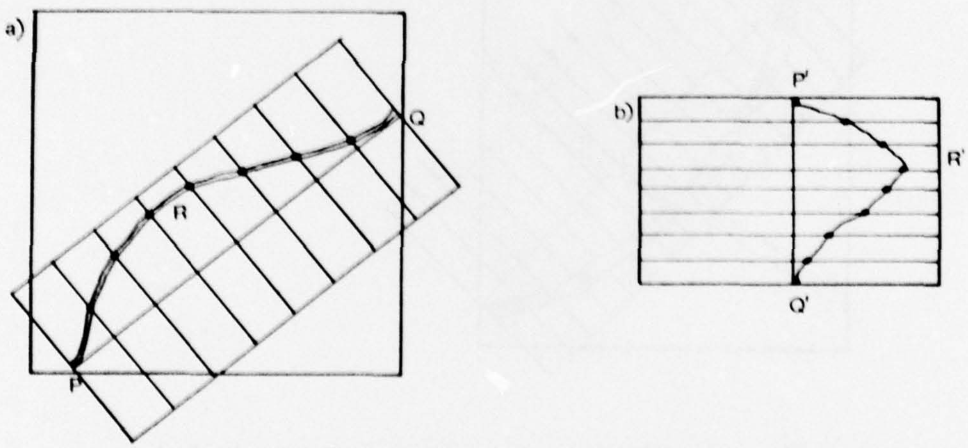


Fig. 6: Rectangle containing the road (a); transformed slices of the rectangle (b)

The search for parts of the sample lines which may belong to the road concentrates on the detection of certain features of the road:

- the contrast between the road and the surounding area at both sides of the road
- the constant grey level of the pixels on the cross section of the road
- the correspondence of the features of the roads at adjecent sample lines

Those parts of the sample lines which are definitely recognized as points of the road, are transformed back into the original coordinate system of the image and define a polygon to approximate the course of the road.

Note that, due to the interpolation, it is not essential to evaluate <u>all</u> visible parts of the road. Thus, the procedure is able to extract roads which may be disturbed by intersecting roads, or occluded by bridges or trees (see fig. 7). The number of slices within the rectangle depends on the length of the section of the road and on the curvature of the road as well as on the accuracy required (see section 4 for a more detailed description of this method).

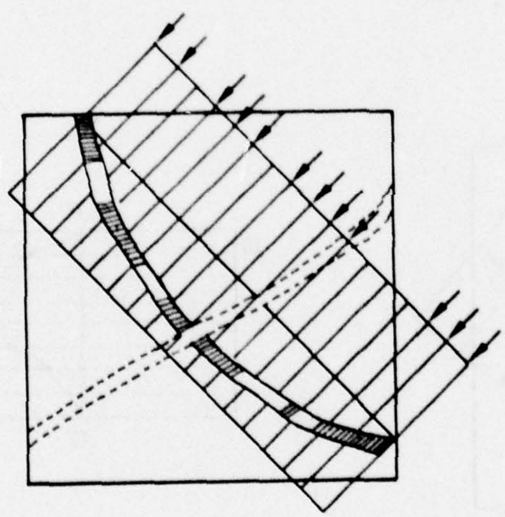


Fig. 7: Slices of successful recognition of the road (see arrows)

4. Detailed description of random method

When we started to develop a method which should be able to find roads in aerial images in spite of the road being partially hidden or invisible we guessed that we could base on two features of a special road [5] .

a) the grey values G are within a reasonable tolerance T
b) the width W of the road is nearly constant

To overcome faint or invisible parts of roads and to reduce the set of data to be processed, the problem was modified to finding parts of roads within rectangular areas of interest (see also 3.2). A proper choice of these rectangles can guarantee small width to length ratios resulting in small areas with only a limited number of pixels to be processed (fig. 8).

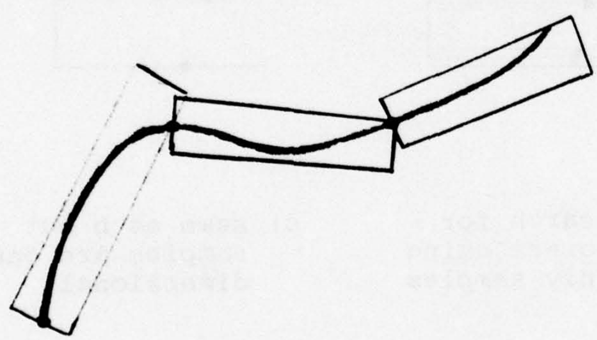
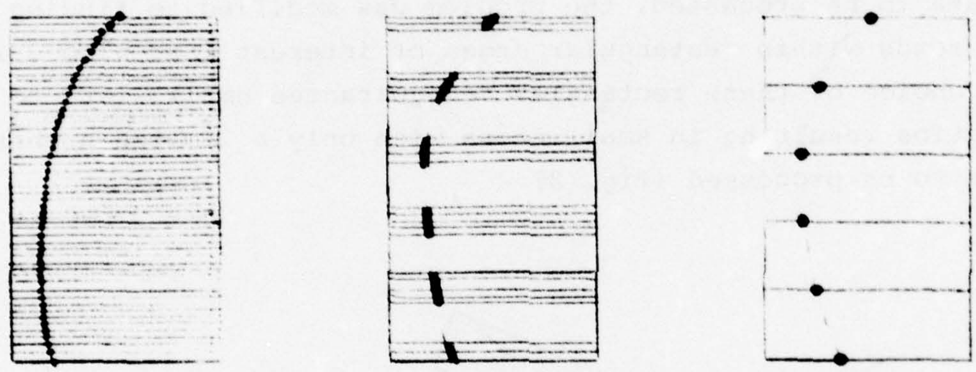


figure 8: part of a road approximated by three rectangular areas of interest

A systematic search and processing of data within the rectangle could now be started to find all points on the road (fig. 9a). Yet a good part of the result is redundant as the curvature of the road within the area of interest is small (no turns) by definition. In other words: A smaller number of vertices could as well approximate the segment of the road appropriately (fig. 9b).

For this purpose only a limited number of samples is taken from the rectangle not considering the course of the road between two adjacent samples.

Experience has shown that it is sufficient to consider sample lines instead of 2D-sample areas. Thus, the two-dimensional problem to find segments of roads in a rectangular area can be reduced to finding points of the road on one-dimensional sample lines (fig. 9c).



a) systematic and complete search for points on the road

b) search for points using only samples

c) same as b but samples are one-dimensional

figure 9: area of interest containing a road segment

Advantages and limits of this sampling method are obvious. Small gaps accidentally located between two (sample) lines are not even registered. Sampling of a road crossing may possibly fail to yield a point on the road (fig. 10),but does not yield incorrect results.

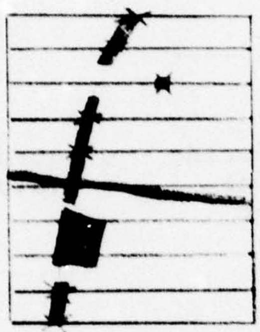
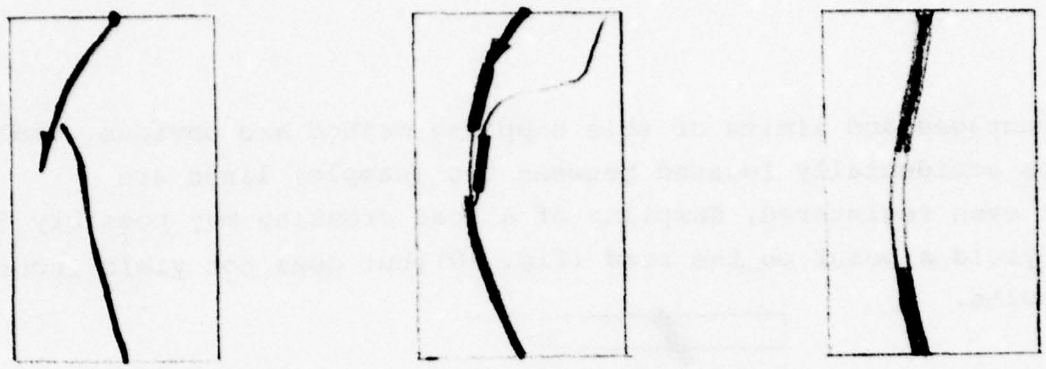


figure 10: points found on a partially hidden road using constant width and grey value criterion

Road segments touching areas with nearly the same grey value cannot be recognized. Patches with size and grey value similar to those of the road located nearby the road may yield incorrect results.

Considering this, a first series of attempts was made. We started from the center of the first sampling line where the road should pass using a cone as area of expectation for the next point on the road. This procedure was refined by adjusting the grey value to be expected to the grey value of the actually found point on the road. Such deviations of the grey level along the road could be compensated within a limited range. If no segment of road was found the range of expectation was searched for grey level intervals greater than W. If this search was successful the road was supposed to being tangent to an area of the same grey value as the road. This method had 3 serious drawbacks which are illustrated in figure 11



a) deadlock situation

b) interfering parallel contour

c) abrupt changes of grey values along the road

figure 11

A deadlock situation may occur in road following if a short appendix is more distinct than the road itself (a). Close-by parallel contours may cause the procedure to leave the wanted road (b). Abrupt changes of grey values along the road cannot be processed and the procedure may stop (c).

Another approach was made which proved to be more promising. It is described in detail. Fundamental differences to the method described above are:

- the grey value at a point is only of inferior importance
- the grey value profile in a line is examined
- possible candidates are selected (this could be done randomly) i.e. it does not matter whether line number l is processed before line number l' or v.v.)
- the number of candidates is reduced to one per sample line considering connectivity and smoothness between neighbouring lines.

The first step is to define the rectangle and the number of samples to be taken. For this purpose the operator has to identify a point on the road which serves as a starting point.

This could be done via light pen or trackball. The length and direction of the rectangle is introduced to the system by means of a second point which may not necessarily be part of the road. The width of the rectangle, the number of samples, and the estimated width of the road (number of pixels) are entered via function keyboard or as numbers from the teletype (fig. 12):

```
enter name of image file                          *
enter image size (e.g. 1024x1024 pixels)          *
enter picture scale (f.e. 1:44000)                *

provide width of rectangle                        **
   "    number of sample lines                    **
   "    width of road                             **
   "    2 points on rectangle                     ***

extract road segment

  * done once per image
 ** changed if necessary
*** once per rectangle
```

Figure 12: provision of parameters

Due to the limited amount of data to be processed it will generally be possible to keep all sample lines of a rectangle simultaneously in core. This allows fast and repeated processing of the original grey value data. For this purpose a normalized matrix is computed with the number of rows $l_{\emptyset}$ corresponding to the number of lines and the number of columns $k_{\emptyset}$ corresponding to the number of pixels along a line (fig 13).

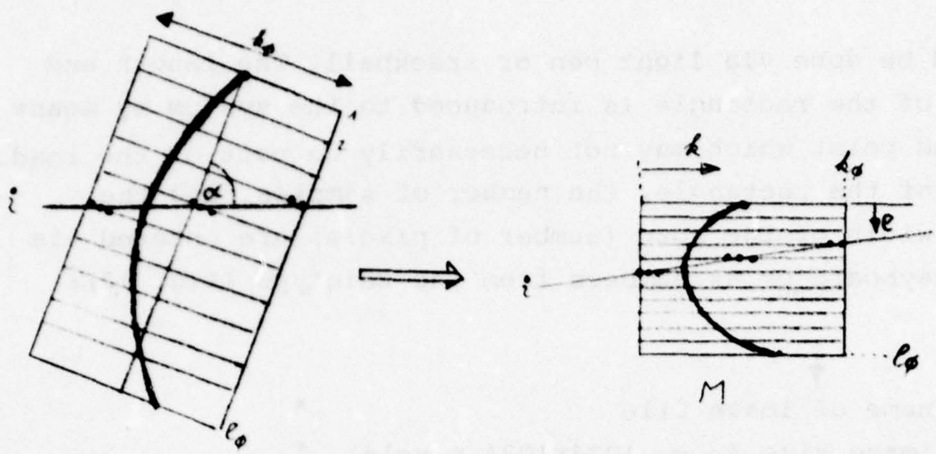


figure 13: normalized matrix M containing the sample lines

As data transfer from mass storage to core takes the bulk of processing time care has to be taken to access each image line only once. Intersection of an image line i (fig. 13) may yield from 1 up to k_ϕ intersecting points with a sample line l depending on the slope α of the rectangle

$\alpha < 45^\circ$	1 point of intersection per line
$45^\circ < \alpha < 90^\circ$	k ($k<k_\phi$) points of intersection
$\alpha = 90^\circ$	k_ϕ points of intersection

Each image line i may additionally intersect with more than one sample line. The transformation algorithm has to evaluate all these points of intersection with line i and store them in the normalized matrix M. All further processing is based on data contained in M.

Evaluation of points on the road segment is done mainly in 2 steps:

a) processing single lines; each point on a line is assigned a probability ph to belong to the road (horizontal probability)

b) points with high probability ph are examined whether acceptable neighbouring points exist in other lines (vertical probability pv)

In each line a single point with maximum probability p = f (ph, pv) is retained.

<u>Evaluation of horizontal probability ph</u>

Each point of a horizontal line is compared with its neighbours in this line. Depending on the local profile of the grey level diagram ph is evaluated.

$$ph = d2 * C \qquad (1)$$

d2 is the second order difference of the actual point with up to 3 neighbours to the right and to the left (fig. 14). No more neighbours are considered if a point of return in the grey value diagramm is reached (first order difference changes sign). Thus the contrast of each point with its immediate neighbouring points in both directions is considered while more distant points are ignored.

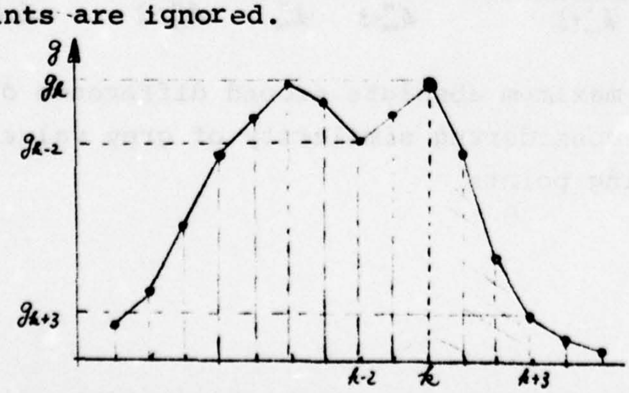


figure 14: example for evaluation of second order difference for point k

f.e. in fig. 14:

$$d2_k = (g_k - g_{k-2}) - (g_{k+3} - g_k) = 2g_k - (g_{k-2} + g_{k+3})$$

if

$$\mathrm{sign}(g_k - g_{k-1}) = \mathrm{sign}(g_{k-1} - g_{k-2}) \neq \mathrm{sign}(g_{k-2} - g_{k-3})$$

and

$$\mathrm{sign}\ (g_{k+1} - g_k) = \mathrm{sign}(g_{k+2} - g_{k+1}) = \mathrm{sign}(g_{k+3} - g_{k+2})$$

The absolute value of d2 is high on edges or on (positive or negative) peaks of limited width as shown in figure 15. This reflects best situations in the test material, where the profile of roads is in most cases a peak containing only a few pixels (1-5 depending on picture scale and appearance of the road).

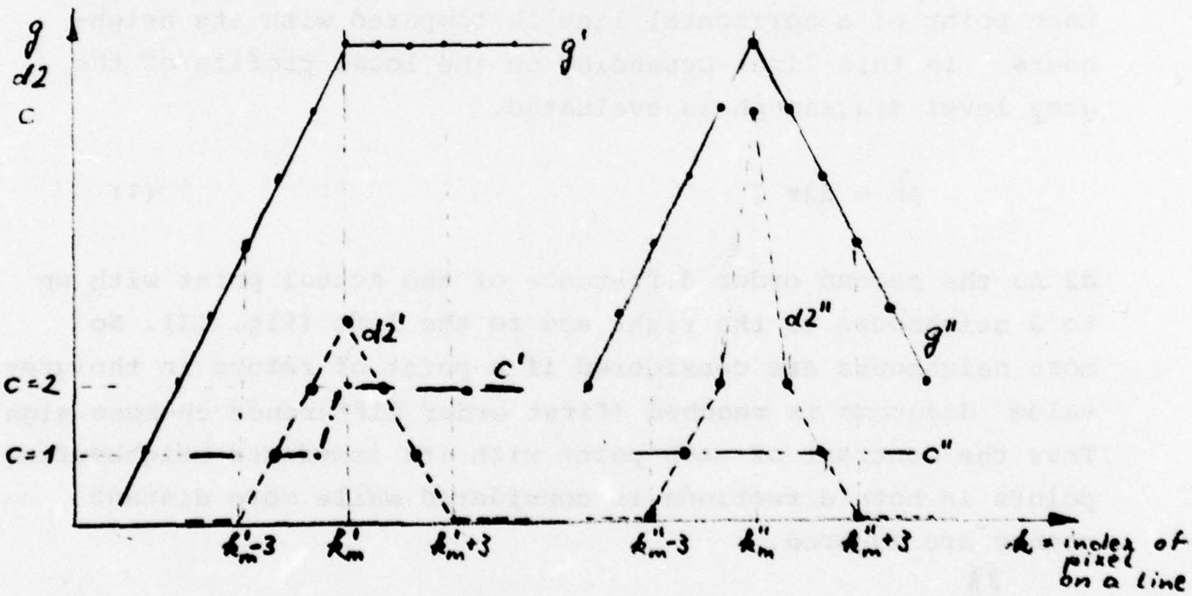


figure 15: examples for maximum absolute second difference d2 and factor C considerung similarity of grey values of neighbouring points

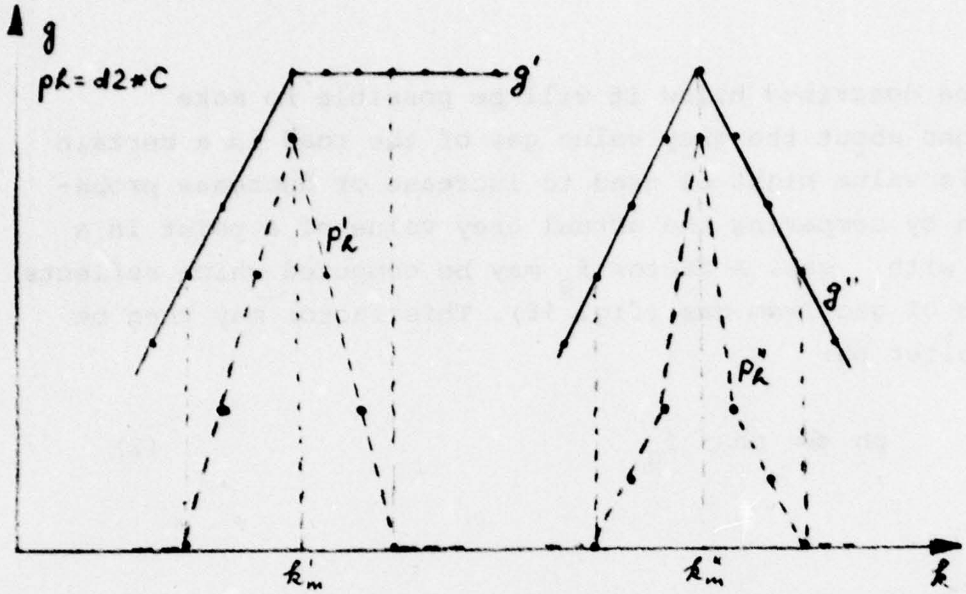


figure 16: example for horizontal probability ph of points to belong to a road

To take into account a local constancy of grey values a factor C is introduced. This factor may be used to increase probability ph if a neighbouring point exists either at k-1 or k+1 with a grey value similar to p_k (fig. 15).

The factor C is used with an upper and lower bound (fig. 17). The upper bound is chosen as c = 2 in order to get $d2'*C'|_{k=k'_m} = d2''*C''|_{k=k''_m}$ (fig. 16). The lower bound C=1 is chosen to retain high probabilities for peaks (fig. 16).

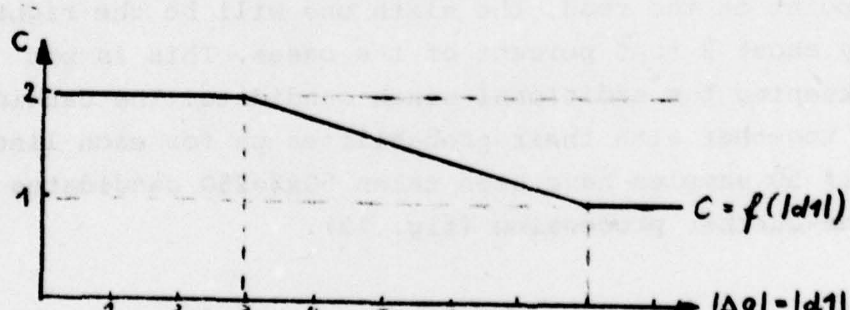


figure 17: factor C as function of first order difference between neighbouring points

As will be described below it will be possible to make assumptions about the grey value gas of the road in a certain line. This value might be used to increase or decrease probability ph by comparing the actual grey value of a point in a line gac with gas. A factor f_g may be computed which reflects deviation of gac from gas (fig. 18). This factor may then be used to alter ph:

$$ph \Leftarrow ph \cdot f_g \qquad (2)$$

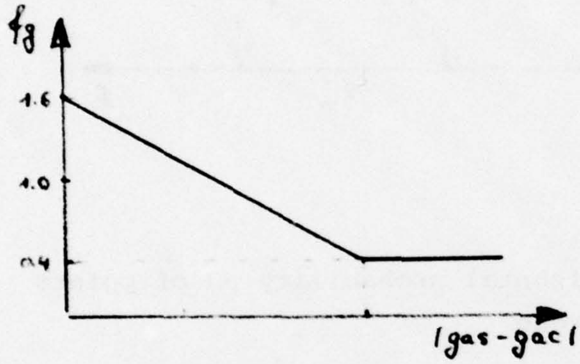
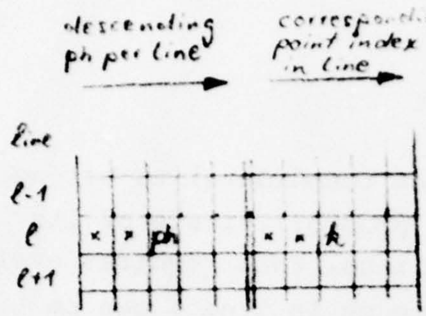


figure 18: factor f_g as a function of grey value deviation from a reference grey value gas

Points with the highest values ph are considered to be the best candidates to belong to the road. Adjacent high valued points are merged to a single candidate. To reduce amount of data to be processed in the next step only the best five candidates in each line are retained. The number of five points has been found to be reasonable by experience. It has turned out that if the five best candidates from (f.e.) 100 points in a line do <u>not</u> involve a point on the road, the sixth one will be the right one in only about 3 to 5 percent of the cases. This is not worthwile keeping the additional sixth candidate. The candidates are stored together with their probabilites ph for each line, such that if 50 samples have been taken 50x5=250 candidates are retained for further processing (fig. 19).



candidate with index k in line l has probability ph to belong to the road. There are two points in l with higher probabilities

figure 19: tabel of the 5 maximum horizontal probabilities per line

Figure 20 shows an example for the five candidates per line in the right part. In the left part these candidates are overlayed to the normalized matrix M. Brightness of the candidates is proportional to ph.

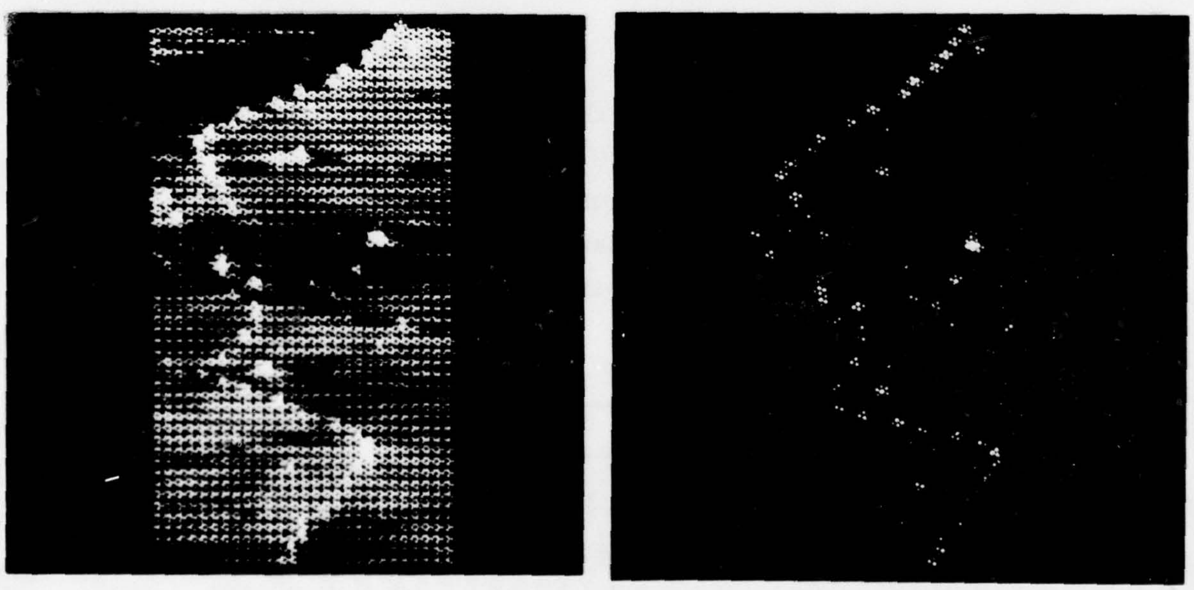


Fig. 20: example for the best 5 candidates per line

Evaluation of vertical probability pv

The vertical probability pv of a point (candidate) to belong to the road is a function of overall probabilities p of its best fitting neighbours in adjacent lines. This requires evaluation of p=f(ph,pv) in line l-1 before pv in line l can be computed. This neighbourhood of a candidate is defined by a cone as shown in figure 21. The angle of

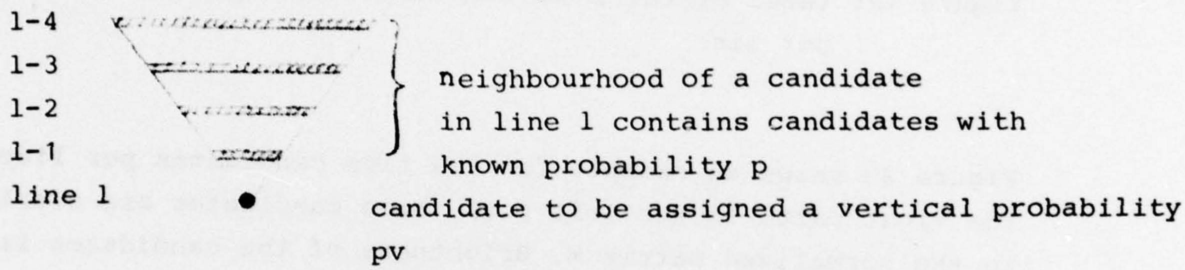


figure 21: cone in which vertical neighbourhood of points is investigated

the cone defines (together with the ratio of number of sample lines to the total of possible lines) the maximum slope the road may have. The "best" neighbours are found by constructing all possible polygons which pass each line from l-4 to l exactly once using as many points as being available (fig. 22).

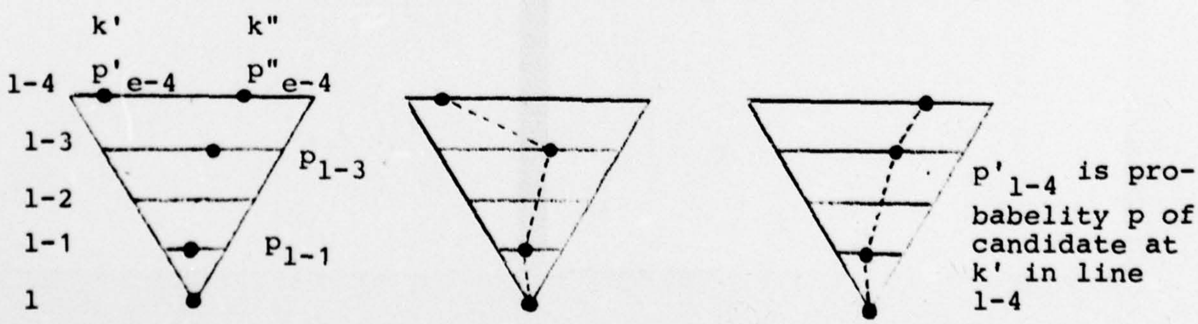


figure 22: polygons for evaluation of pv

The polygons are each valued according to whether

a) some candidate exists in a line or not
b) a triplet of candidates including the one in line l
is nearly collinear

Mere existence of neighbouring candidates yields a component pv1 for the vertical probability according to

$$pv1 = \sum_{n=1}^{4} (5-n)p_{l-n} \qquad (3)$$

p_{l-n} is the probability of the vertex of the polygon in line (l-n). It can be seen that existence of candidates near line l (actual candidate) with high probabilities p_{l-n} yields a good value for pv1. Example in figure 22 yields

$$pv1' = 4 * p_{l-1} + 2 * p_{l-3} + p_{l-4}$$

$$pv1" = 4 * p_{l-1} + 2 * p_{l-3} + p"_{l-4}$$

If f.e. candidate with index k" in l-4 has already had a "better" neighbourhood than the one with index k' ($p"_{l-4} > p'_{l-4}$), pv1" will become greater than pv1'. In this way vertical connections between candidates are proliferated from "top" to "bottom" resulting in increasing probabilities along a chain of points.

To take into account smoothness of the road local collinearity is considered by testing all possible triplets of candidates in the vertical neighbourhood which include the actual candidate. This results in a second component pv2 where

$$pv2 = \sum_{m=1}^{n-1} \sum_{n=2}^{4} v_m \cdot \quad (p_{a-m} + p_{a-n})/2 \qquad (4)$$

v_m is a measure for the vicinity of a candidate in line a-m to the straight line defined by candidates in lines a and a-n (fig. 23). It is defined as

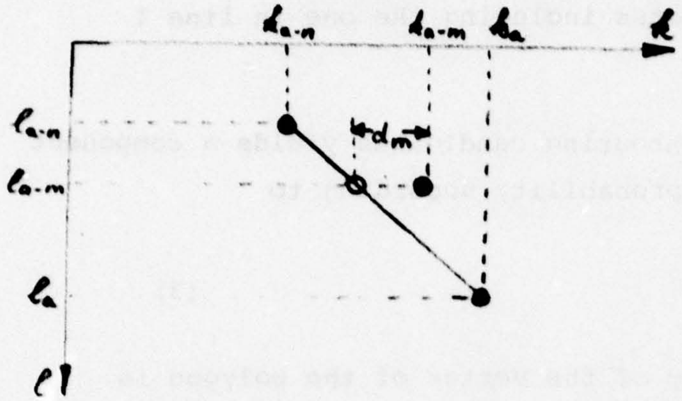


figure 23: horizontal deviation d_m of a candidate

$$v_m = |d_{max} - d_m| \quad \text{for } |d_m| < d_{max}$$

and

$$v_m = \emptyset \quad \text{for } |d_m| \geq d_{max} \tag{5}$$

d_m is the deviation of the candidate from the straight line and d_{max} is the maximum deviation tolerated (f.e. d_{max}=3). Triplets with deviations greater or equal d_{max} will yield no contributions to pv2.

d_m is computed as

$$d_m = (k_{a-n} \cdot m + (n-m) \cdot k_a)/n - k_{a-m} \tag{6}$$

where m = 1, n-1 and n = 2,4

The measure v_m is multiplied with the average of the probabilities fo the two points whose probabilities we do already know (see e.g. (4)).

The probability pv2 may than consist of up to 6 terms according to 5 lines considered (fig. 24).

triplet no:	line no: 1	1-1	1-2	1-3	1-4
1	x	x	x		
2	x	x		x	
3	x	x			x
4	x		x	x	
5	x		x		x
6	x			x	x

figure 24: The six triplets which are tested for collinearity in 5 lines

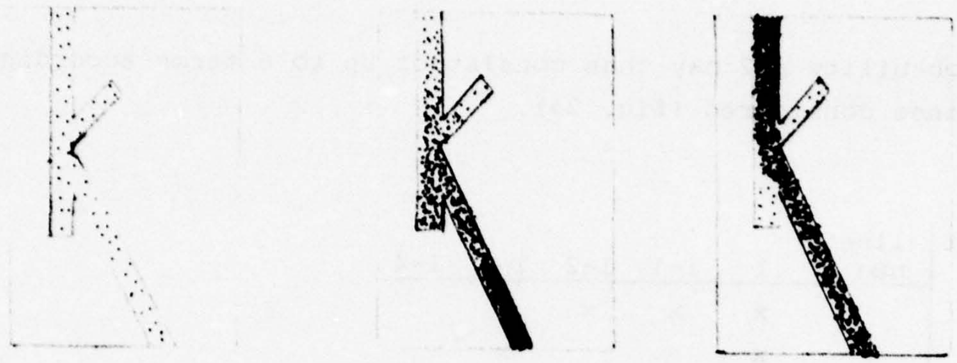
As stated above pv1 and pv2 are computed for each combination of points within the cone and with assumptions as made above. The vertical probability of the actual point is then

$$pv = pv1 + pv2 \qquad (7)$$

The maximum value of pv is finally used and added to the horizontal probability ph of the point yielding

$$p = ph + pv \qquad (8)$$

This is done in forward direction starting from the first line until the last line is reached. A road configuration as shown in figure 25a would result in candidates with varying probability p as shown in figure 25b. To suppress appendices symmetrically, p has to be computed once again from bottom to top starting from the last line resulting in probabilities shown in figure 25c.



a) candidates with high values ph

b) high values p after top to bottom evaluation of pv

c) same as b) but additional bottom to top processing

figure 25: example for forward and backward evaluation of pv

In order to limit the growing of p along a smooth chain of points and to weight influence of ph, pv1 and pv2 some constants have been introduced. pv1 may contribute 10 portions (eq. (3)) while pv2 may contribute 6 portions only (eq. (4), fig. 24). On the other hand collinearity of neighbouring points is a better hint for road segments than the mere existence of these points. It has turned out to be useful to increase influence of collinearity by 50 %. pv and ph have been given equal influence. Therefore,

$$pv1 \leftarrow pv1/10$$
$$pv2 \leftarrow pv2/6 \cdot 1.5$$
$$pv \leftarrow (pv1+pv2)/2$$
$$p \leftarrow (pv+ph)/2$$

results in

$$p = ((pv1/10+pv2/6 \cdot 1.5)/2+ph)/2 \qquad (9)$$

Equation (9) yields probabilities which are generally high or low enough to decide whether a candidate in a line is the very one which we have been looking for. At this point in each line the candidate with the highest probability is selected. Now we

have got a polygon with one vertex in each line approximating the road. Results from test images are good enough not to implement sophisticated methods to automatically correct the course of the road. Instead, correction is accomplished in two simple steps

a) single points within a smooth environment are corrected automatically
b) other bad results have to be corrected interactively at the screen

Correction of points

5 neighbouring candidates, as shown in figure 26, are considered. As three points define a second order curve, one can be quite sure that a parabolic segment of road exists if even four neighbouring points are situated on a parabola. A fifth point between can then be adjusted to the parabola (figure 26). In all examples shown in the chapter "results", only this simple automatic method to correct points has been used if not stated otherwise. If there are results which cannot be tolerated or corrected automatically the user in our implemented system has the possibility to delete or update parts of the road segment explicitely. For this purpose the resulting polygon is displayed twice in full brightness: against a dark background, and secondly overlayed to the matrix M as was shown in figure 20. The user can decide in which of the two representations he will delete or update points.

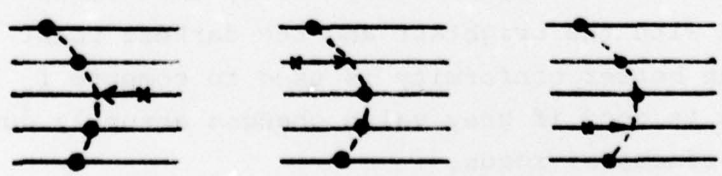


figure 26: correction of single points

Assumptions on grey values

It has been stated above that knowledge about the grey value of the road segment could be used to increase horizontal probability ph. As it is very difficult to get exact grey values, various assumptions on them are made. On the basis of these assumptions different results (polygons approximating the road segment) can be evaluated and compared to select the best of them. This proceeding is possible and reasonable as mere computing time to get an approximating polygon in a rectangle of fifty lines with 100 points each, is only about 1 to 2 seconds. This is true although all programs are written in FORTRAN and are not optimized to a high degree.

In the programming system there exist two modes by which assumptions about the grey value can be made.

a) an assumption is made by the operator (interpreter). The corresponding polygon is evaluated.
b) all five possible assumptions are made automatically and successively by the system and all polygons are evaluated and compared.

Possible assumptions about grey values are as follows:

1. The grey value gas (fig. 18) of the road is assumed to be the highest one existing in each line (road appearing bright compared to background)
2. gas is the lowest grey value in each line (dark road)
3. gas is the lowest or the highest grey value, that means gac is compared with the brightest and the darkest point in the line. The better conformity is used to compute f_g (2). This assumption is good if grey value changes abruptly due to different surfaces of roads.
4. gas is the grey value of the best candidate in the first line. As the starting point is defined interactively it is possible to hit a point close to the road with the cursor. Therefore only a very restricted range ground the cursor position is searched for candidates. Only the best one (instead of 5

in the other lines) is taken as the candidate in the first line. This assumption for gas is good for homogeneous grey values on the surface of the road.

5. No assumption for gas is made. Factor f_g is taken as f_g=1.

If various assumptions have been made, the best result has to be found. This can easily be done by adding all probabilities p of the candidates. The maximum sum is assumed to correspond to the best result as it reflects best appearance of the profile of the road and coherence between candidates.

The overall procedure is shown in figure 27.

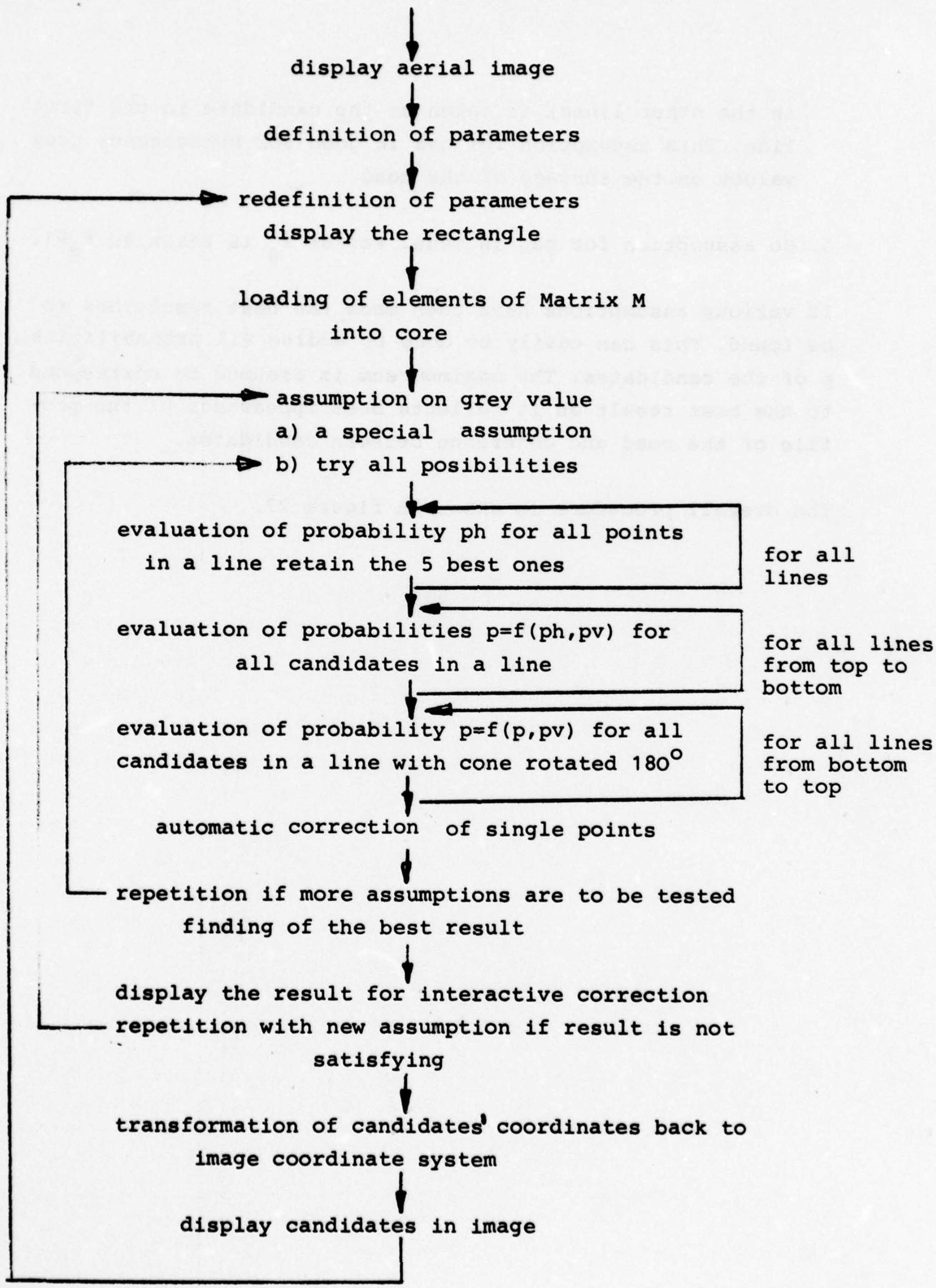


figure 27: overall procedure for road extraction

5. Results

In this section results are discussed which were obtained using the random method to extract segments of roads. Sections of photographs with a scale of 1:74000 were used as test material. These images were displayed on a Comtal display with a resolution of 512 x 512 pixels (9 bit spatial resolution). The processing was done using a digitized version of the same image with a better 11 bit resolution (2048 x 2048 pixels). Roads had an average width of 3 to 4 pixels. Where the appearance of the road was good, even the 9 bit resolution was good enough to provide 1 pixel which could be distinguished from the surrounding of the road.

Figure 28 shows a section displayed on the screen. A rectangle was defined in the upper left of the image surrounding a bright road together with a darker object, possibly a ditch. Details can be recognized better looking at the display of the normalized matrix M (fig. 29) which was taken from the 11 bit image.

Fig. 28: defining rectangle

Fig. 29: normalized matrix 50 lines, 100 points per line

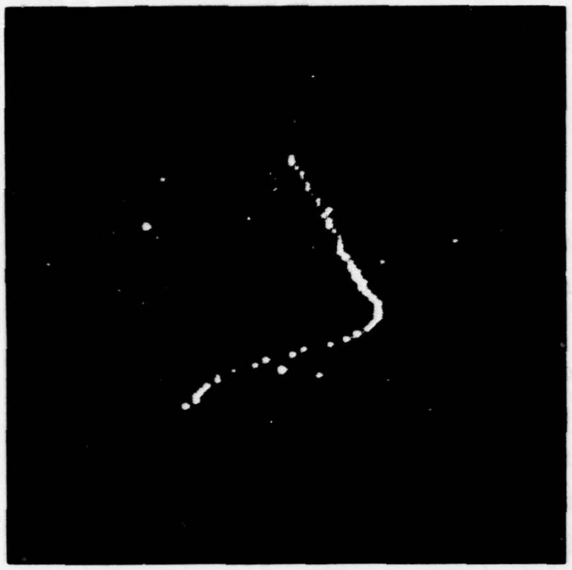


Fig. 30: candidates with gas being bright

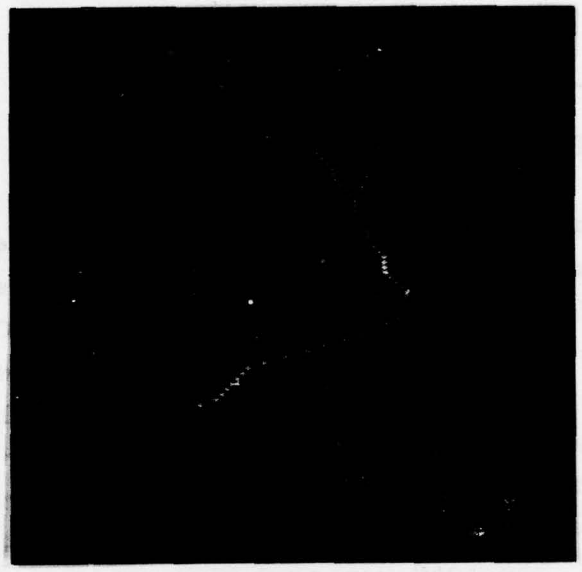


Fig. 31: resulting approximating polygon

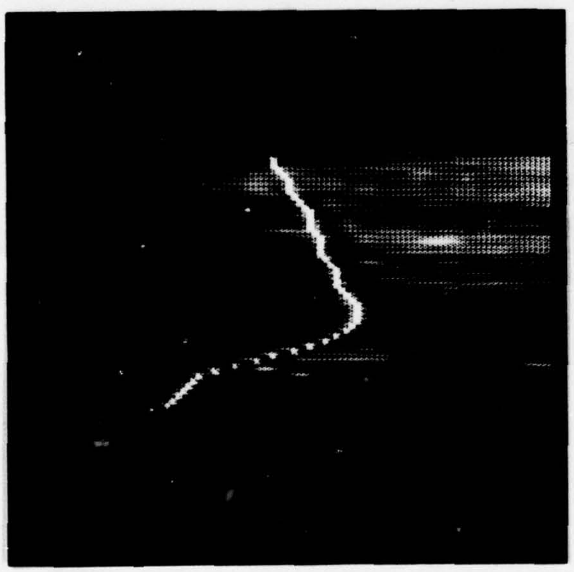


Fig. 32: resulting polygon overlayed to matrix M

In figure 30 five candidates per line are displayed. The brightness of each point is proportional to its horizontal probability ph. It can be seen that even ph for itself yields good results. The final result is shown in figure 31 and 32. After computing the probability p the best point in each line was selected and automatic correction of single points was done. No interactive correction by the operator was neccessary.

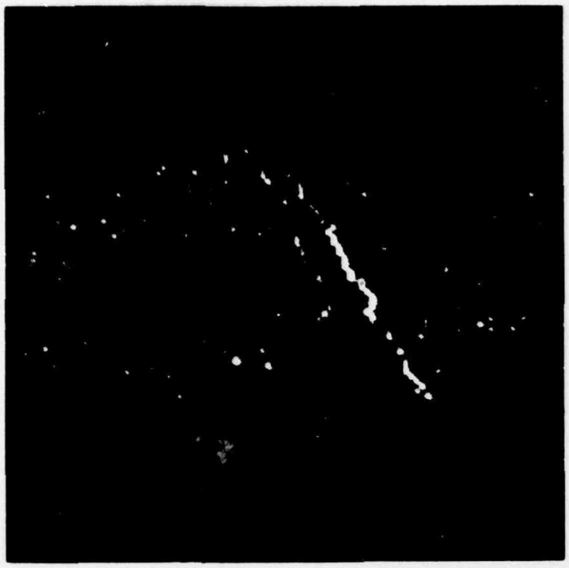


Fig. 33: candidate with gas being dark

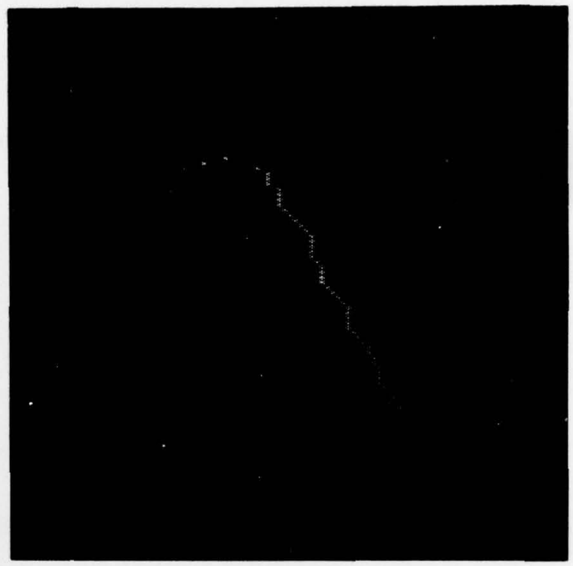


Fig. 34: resulting approximating polygon

Fig. 35: resulting polygon overlayed to matrix M

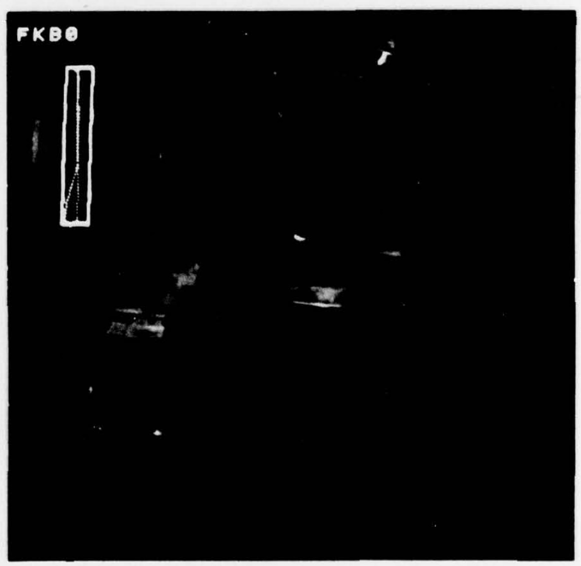


Fig. 36: result of bright road and dark ditch

Figure 33 shows the equivalent of figure 30 but a dark appearance of the object was assumed. The ditch near the road was extracted this way (fig. 34, 35) and transformed back and displayed together with the road extracted before (fig. 36).

The next sequence demonstrates extraction of a road segment which contains 3 crossroads and a darker part where the road is no more visible even in the matrix M which was taken from the 2048 x 2048 image (fig. 37, 38).

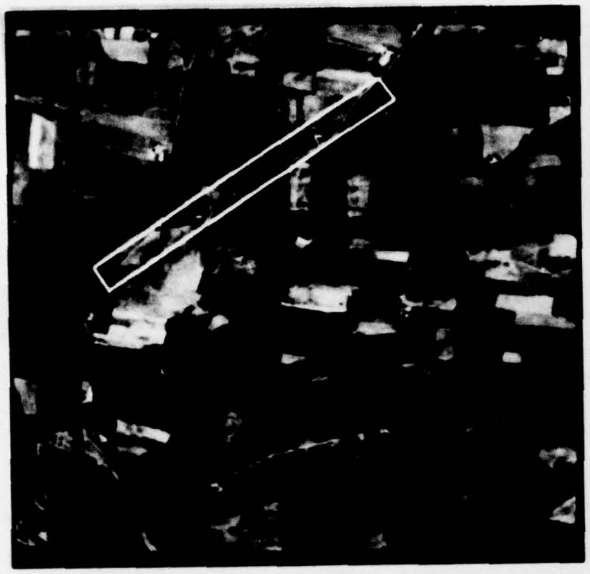


Fig. 37: definition rectangle

Fig. 38: normalized matrix M
50 lines, 100 points per line

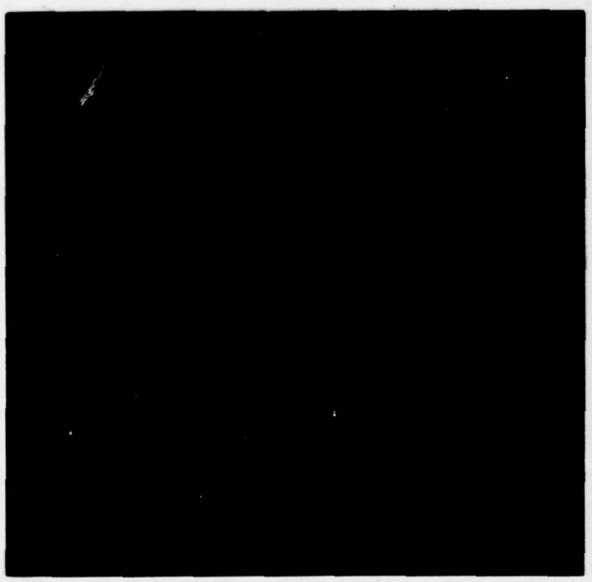


Fig. 39: resulting polygon

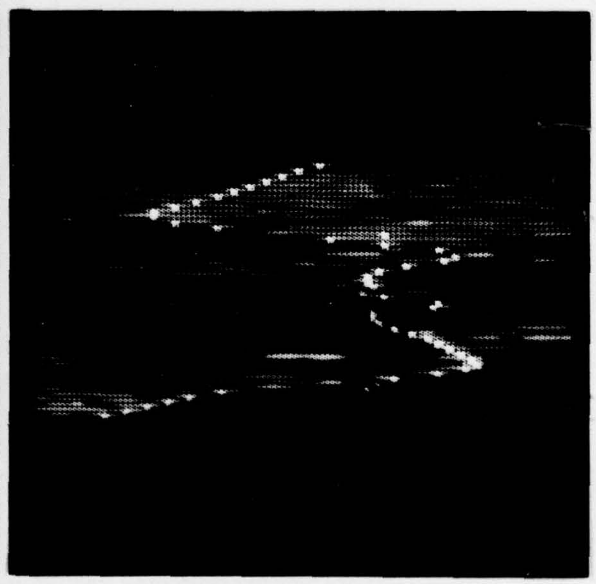


Fig. 40: polygon overlayed to matrix M

Figures 39 and 40 show that three incorrect points remain in the dark portion of the image. This is due to the fact that no candidate at all could be found in this part. Two incorrect points at the lower end of the polygon are caused by exceeding the maximum slope of the polygon. The correct points were discarded because they could not be reached by the cone used to compute the vertical probability pv. Thus the interpreter is forced to chose a greater number of sample lines or to shorten the rectangle. In this case 50 lines had been taken from the rectangle which was about 1200 pixels long, that means only every 24th line has been taken. Nevertheless it was easy to correct the resulting polygon interactively (fig. 41, 42, 43).

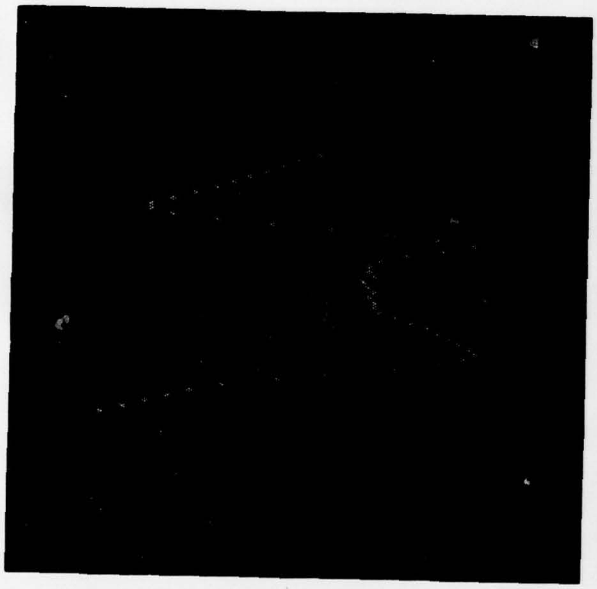


Fig. 41: polygon after interactive correction

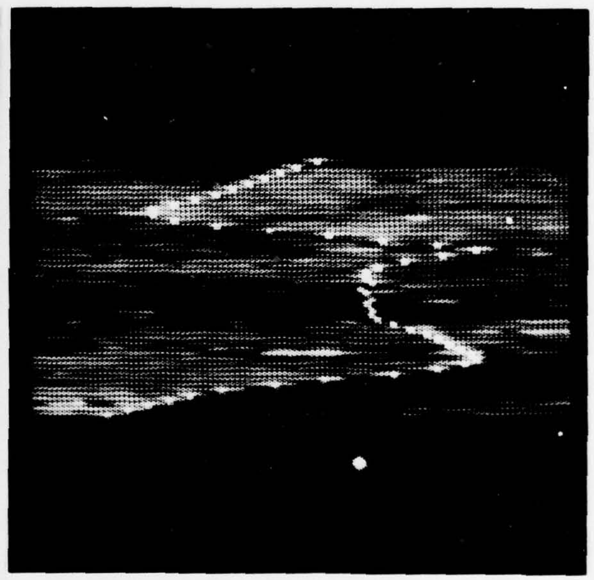


Fig. 42: polygon overlayed to matrix M

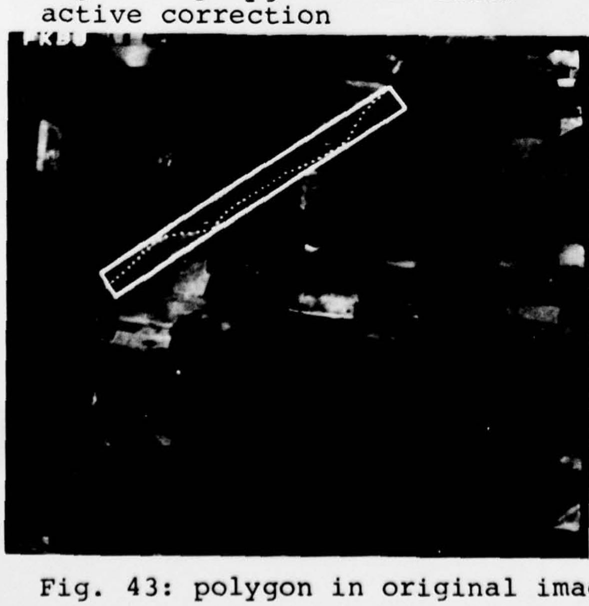


Fig. 43: polygon in original image

The series of figure 44 to figure 50 shows that a result which is not quite as good could be obtained processing the 512x512 image instead of the one with the better resolution.

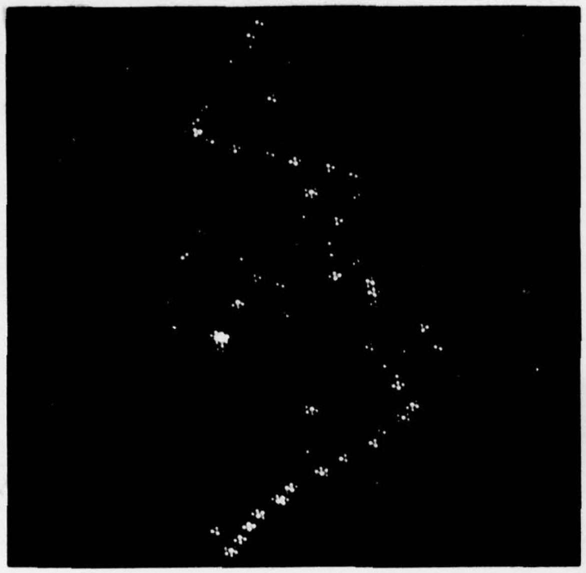


Fig. 44: five candidates per line

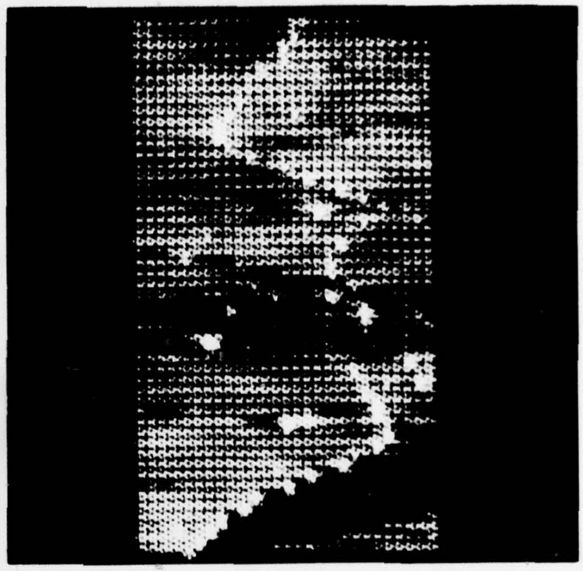


Fig. 45: same as fig. 44 but overlayed to M; 50 lines, 27 points per line

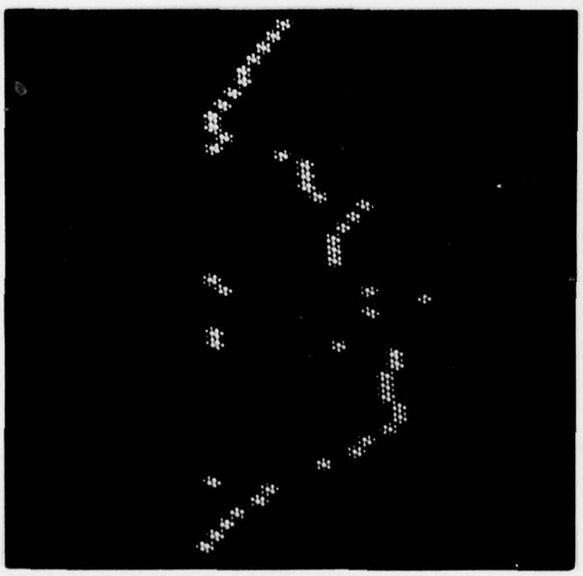


Fig. 46: resulting polygon before correction

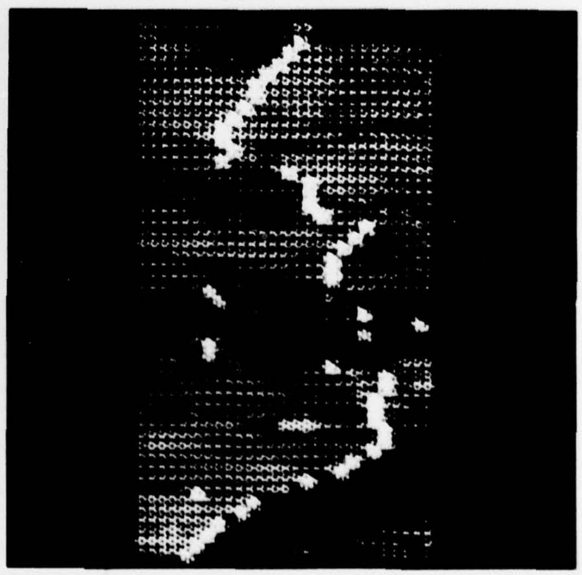


Fig. 47: same as 46 but overlayed to M

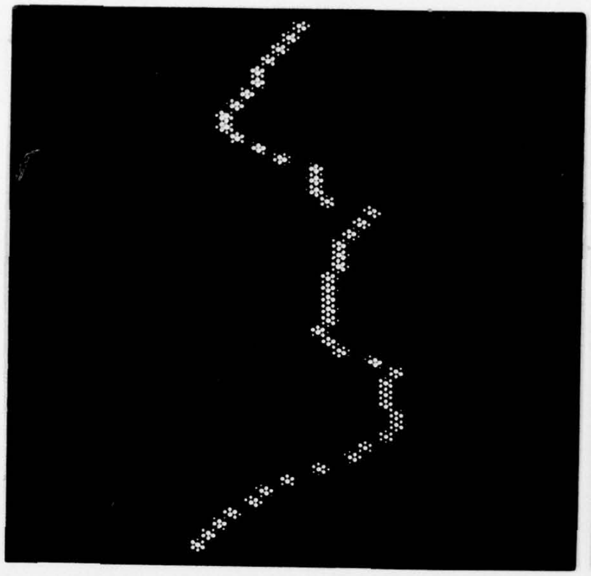


Fig. 48: resulting polygon after interactive correction

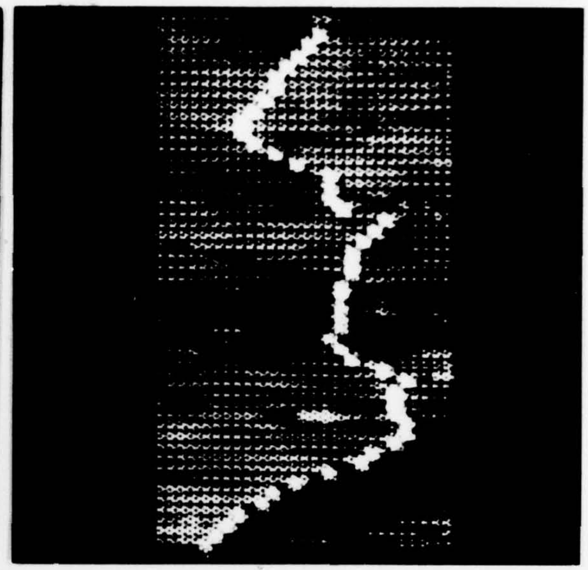


Fig. 49: same as 48 but overlayed to M

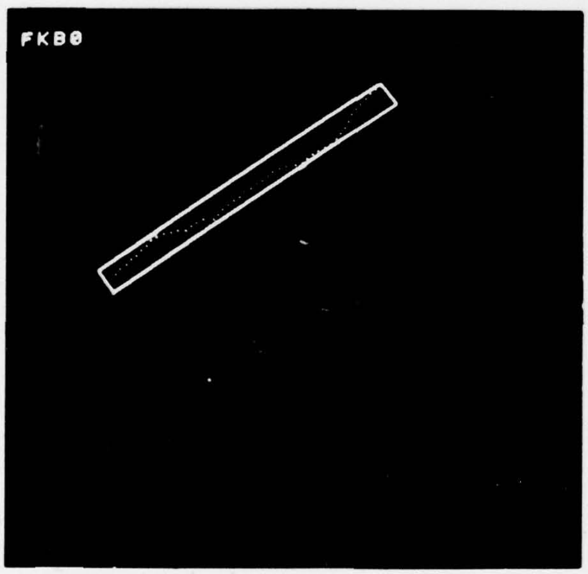


Fig. 50: result in original image

Figure 50 shows that two points have not been corrected although they are located beside the road. Regarding figures 47 and 49 it can be seen that decision could not be made correctly basing upon the display of M.

Figures 51 to 54 demonstrate application of the procedure to another type of object, a dark river. As the object appears clearly in the 512x512 image this image can be taken as the basis for processing.

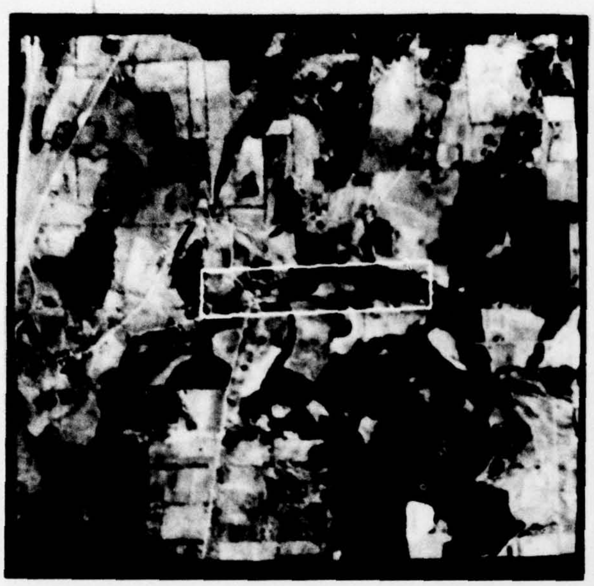


Fig. 51: part of a river to be extracted from a 512x512 image

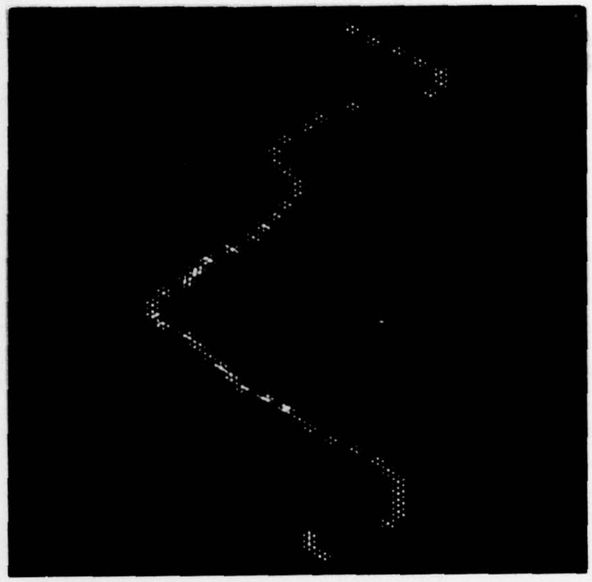


Fig. 52: resulting approximating polygon

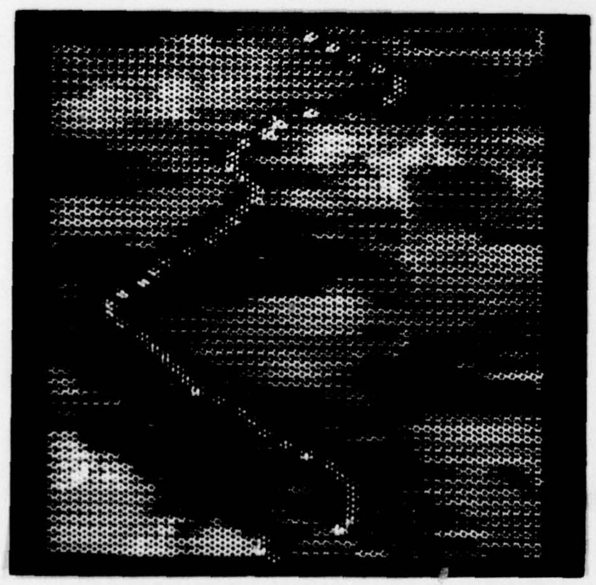


Fig. 53: resulting polygon overlayed to matrix M

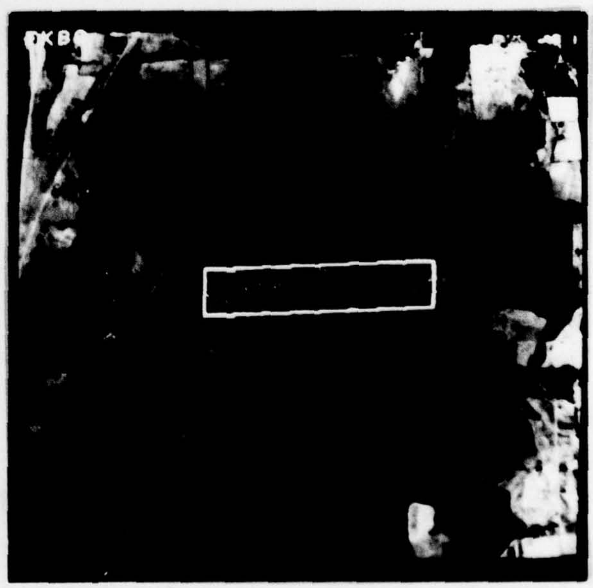


Fig. 54: result in original image

The final example, a road crossing the river, was processed using similar parameters. The results show that both objects can be extracted correctly from the 9 bit resolution image without any interactive correction as at least one contrasting point per line exists (fig. 55 to 58).

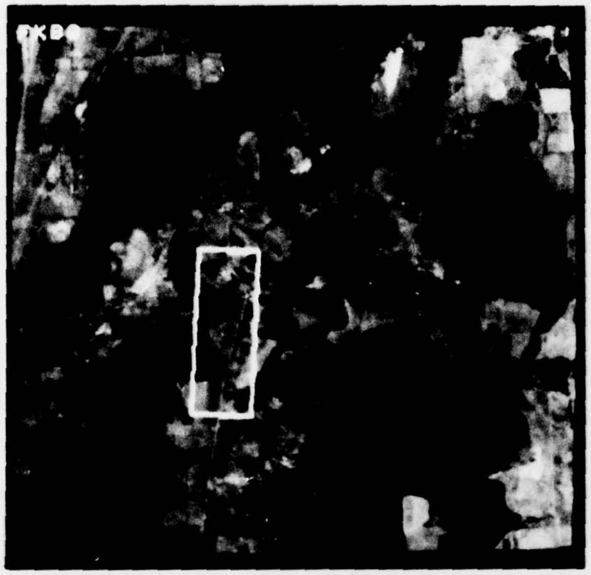


Fig. 55: road crossing the river

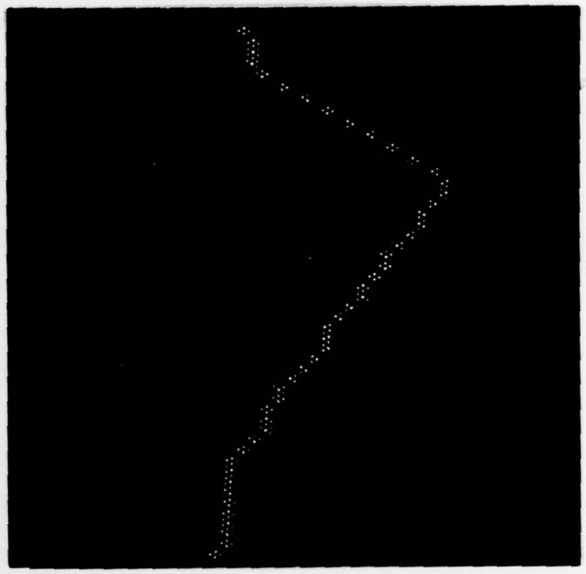


Fig. 56: resulting approximating polygon

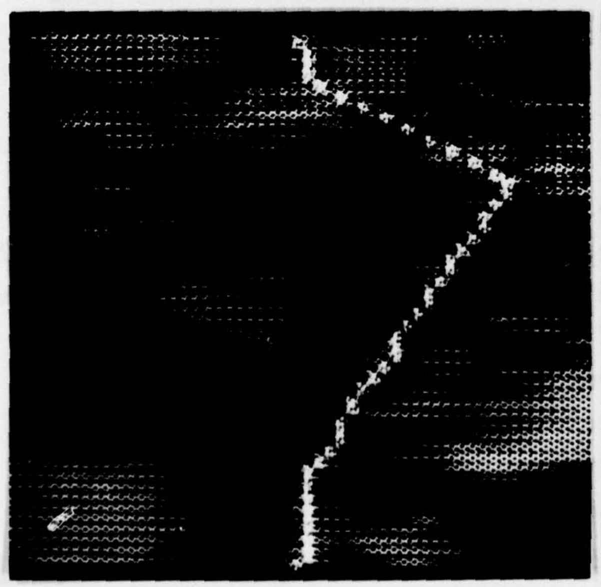


Fig. 57: resulting polygon overlayed to matrix M

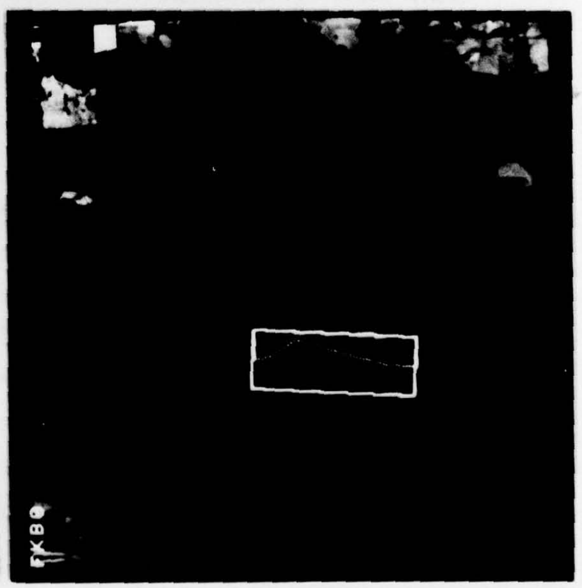


Fig. 58: result in original image

6. Conclusion and discussion of further work

Results in chapter 5 have shown that the procedure described is very suitable to extract roads with a "normal" appearance in the image. That means

- in the greater part of the sample lines at least one pixel must exist with reasonable contrast to its neighbourhood

- extraction of closeby parallel highways needs modification of the procedure as only a single track is extracted at the present state
- varying width of the road will be no problem, but will possibly yield the edge of the road rather than the centre line
- the rectangle and the number of sampling lines have to be chosen such that the slope of the road in the normalized matrix M will not exceed a limit defined by the aperture of the cone. This is neccessary as a horizontal probability can only reasonably be computed if intersection of the road and sample line is unmistakable and candidates in adjacent lines can be reached by the cone for evaluation of vertical probability.

Regarding this, the procedure can as well be applied to objects with similar appearance as roads (rivers f.e.). Fig. 59,60,61,62 show how ambiguities near the object may cause incorrect results. This may happen especially if the defining rectangle is very wide. This could have been avoided if two slender rectangles had been chosen instead of a single wide one. Another approach could be to start the procedure with a slender small rectangle to evaluate a small segment of the road (fig. 63) and start the procedure again by appending <u>automatically</u> a new rectangle.

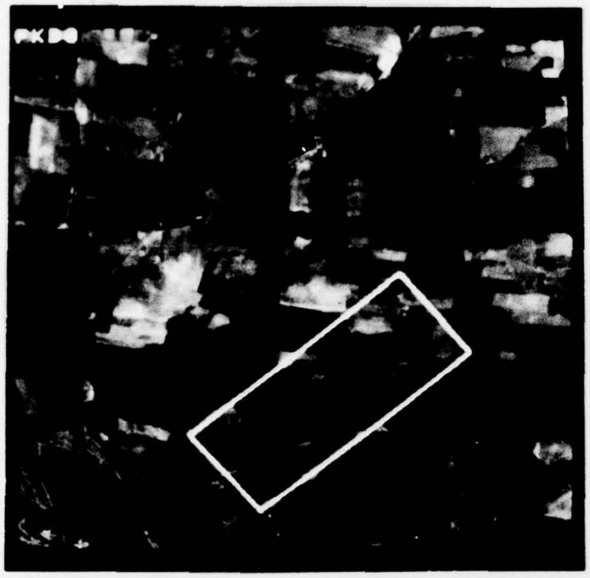


Fig. 59: defining rectangle for a wide area

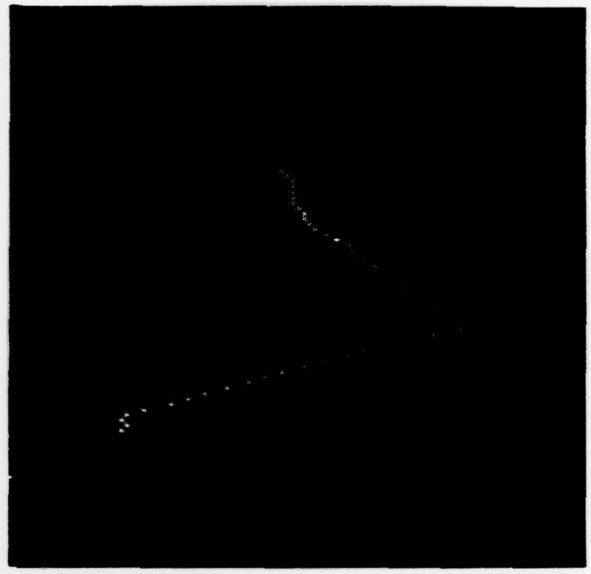


Fig. 60: resulting approximating polygon

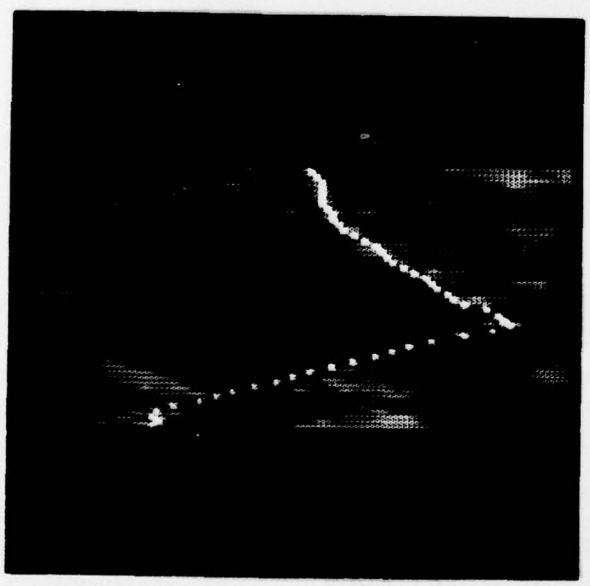


Fig. 61: resulting polygon overlayed to matrix M

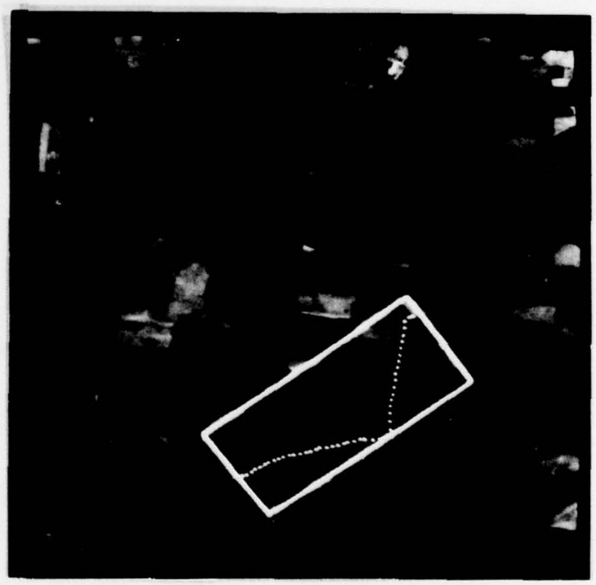


Fig. 62: display in original image shows 3 incorrect points

Fig. 63: defining small rectangle for incremental operating mode

Fig. 64: first rectangle automatically defined

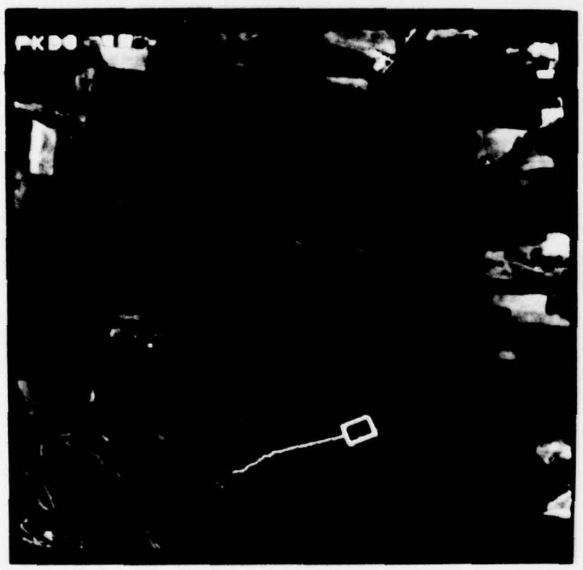


Fig. 65: further step in incremental mode

Fig. 66: final step in incremental mode

The new rectangle uses the endpoint of the small segment already found as its starting point. The endpoint is evaluated with help of the last direction the segment had taken (fig. 64).

We have made first attempts to implement such an incremental operating mode of the random method and have found results promising (fig. 63 to 66 and 67 to 69).

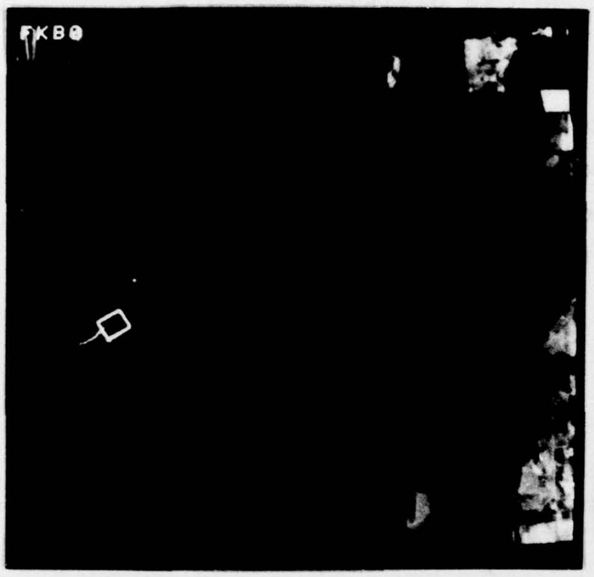


Fig. 67: another example for incremental mode

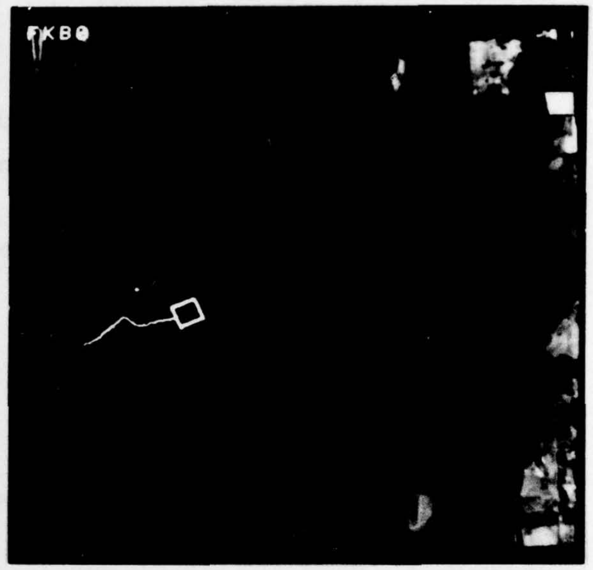


Fig. 68: lower part of the road has been chosen automatically

Fig. 69: stop by the operator

In both examples the end of the procedure was announced by the operator. In fig. 66 no road segment could have been found if the new rectangle is defined by a simple method as described above. In fig. 69 no part of the road was visible beyond the last points found.

Another attempt which could be made to automate road extraction to a higher degree would be to find some of the points on the roads automatically. These points could then be used as starting points instead of interactively defined points at the present state.

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